U.S. DEPARTMENT OF COMMERCE
National Technical Information Service
PB80-128549

Fuel Consumption Measurements-Carbon Balance vs. Flow Meter

(U.S.) Environmental Protection Agency, Ann Arbor, MI

Jul 79

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO.	2.	3. RECI PB80-128549
EPA-AA-SDSB 79-28		

4. TITLE AND SUBTITLE	5. REPORT DATE
Fuel consumption measurements-carbon balance vs. flow meter	July 1979
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S)	8. PERFORMING ORGANIZATION REPORT NO.
Turton, Dale	
9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. PROGRAM ELEMENT NO.
Standards Development & Support Branch Emission Control Technology Division Office of Mobile Source Air Pollution Control U.S. Environmental Protection Agency Ann Arbor, MI 48105	11. CONTRACT/GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS	13. TYPE OF REPORT AND PERIOD COVERED
SAME	Technical
	14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

16. ABSTRACT

In a recent EPA experiment, fuel consumption data was obtained by both the carbon balance method and the fuel flow method. This report was prepared to describe and compare the two methods of measurements. EPA fuel economy measurements are currently obtained by the carbon balance method. Fuel consumption can also be measured by several other methods such as volumetric, fuel flow meters, or gravimetric methods. Accurate comparison between methods must be done statistically and requires a large data base. A recent EPA program which investigated the accuracy of the dynamometer simulation of the speed of a vehicle consisted of numerous repetitive steady state dynamometer tests. This program provided an opportunity to obtain sufficient fuel consumption measurements by both methods for the statistical analysis necessary to detect any difference between the methods.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Fuel consumption Volumetric analysis Chemical analysis Gravimetic analysis	Carbon balance method Fuel flow meters	

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS *(This Report)*	21. NO. OF PAGES
UNLIMITED	UNCLASSIFIED	10
	20. SECURITY CLASS *(This page)* UNCLASSIFIED	22. PRICE A02 - A01

EPA Form 2220-1 (9-73)

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

SDSB 79-28

Technical Report

Fuel Consumption Measurements-
Carbon Balance vs Flow Meter

by

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July 1979

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Standards Development and Support Branch
Emission Control Technology Division
Office of Mobile Source Air Pollution Control
Office of Air, Noise and Radiation
U.S. Environmental Protection Agency

I. Introduction

In a recent EPA experiment, fuel consumption data was obtained by both the carbon balance method and the fuel flow method. Since vehicle fuel economy is an area of present concern, this report was prepared to describe and compare the two methods of measurements.

II. Background

EPA fuel economy measurements are currently obtained by the carbon balance method. This method, in effect, assumes that the carbon atoms emanating in the vehicle exhaust came from the fuel going into the carburetor. Therefore, by measuring the carbon in the exhaust the quantity of fuel consumed can be determined. This approach is used by EPA because all the equipment required is also required for the exhaust emission measurements. The fuel economy can therefore be obtained concurrently with the emissions data at essentially no extra cost.

Fuel consumption can also be measured by several other methods, such as volumetric, fuel flow meters, or gravimetric methods. Any difference between fuel consumption measurements by the available methods is small compared to the total fuel consumed. Therefore, accurate comparison between methods must be done statistically and requires a large data base.

A recent EPA program which investigated the accuracy of the dynamometer simulation of the speed of a vehicle consisted of numerous repetitive steady state dynamometer tests. It provided an ideal opportunity to obtain sufficient fuel consumption measurements by both methods for the statistical analysis necessary to detect any difference between the methods.

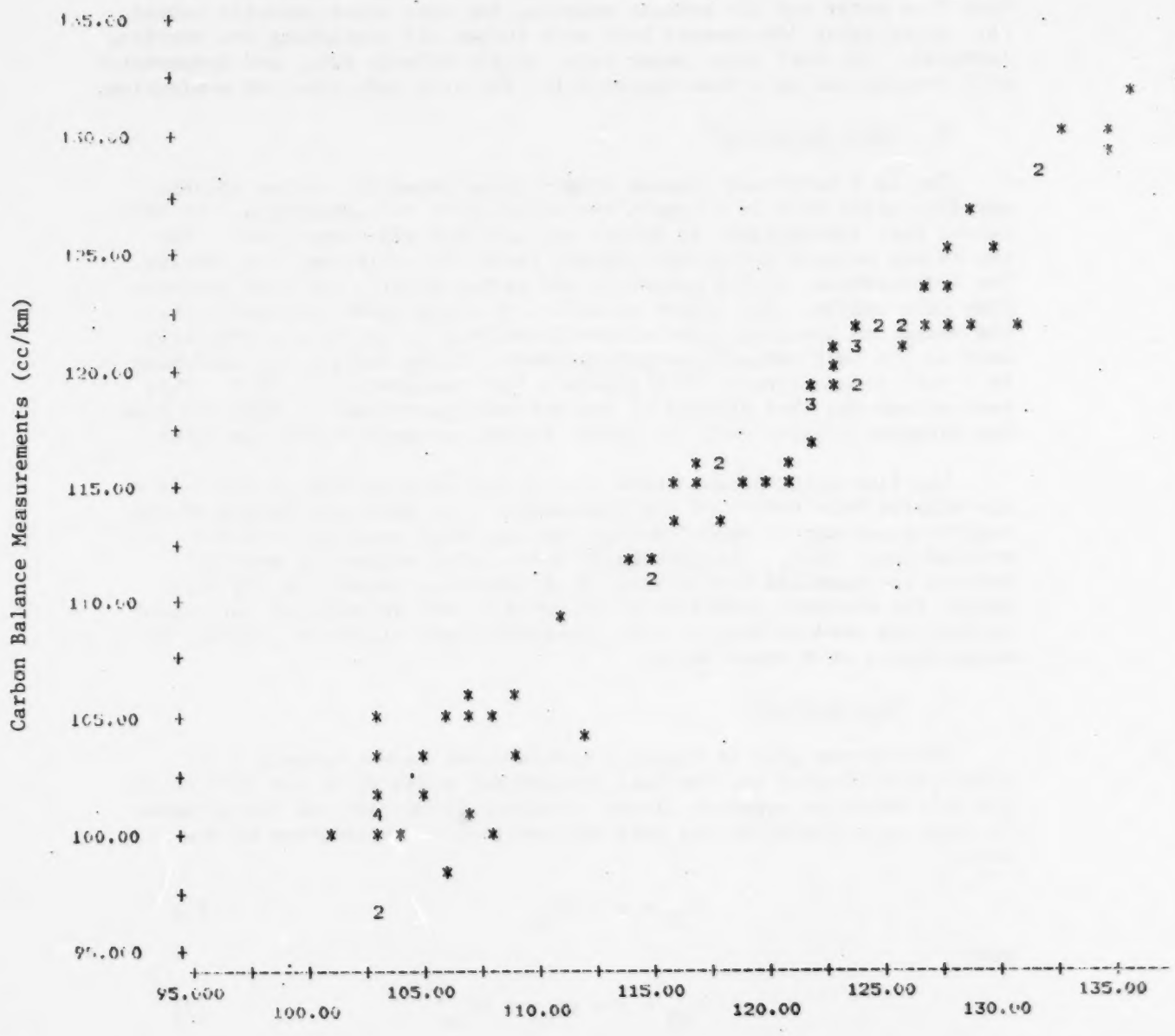
III. Discussion

The experimental program consisted of numerous steady state tests of approximately 5 minutes duration each. During each test the fuel consumption data was obtained by both the carbon balance and fuel flow meter methods. The paired data was then statistically analyzed to compare the two measurement methods. The following subsections describe the experimental program and data analysis in greater detail.

A. Experimental Program

A 1976 Mercury Montego with a 351 V-8 engine was used throughout the experiment. Fuel consumption measurements were obtained at all the combinations of three different dynamometer power absorbtions (10.4, 11.4, 12.4 HP) and three different speeds (40, 50, 55 mph). Thus, nine test points were obtained with this sequence. This sequence was repeated twice, once with the dynamometer rolls coupled and once with the rolls uncoupled. These tests provided 18 fuel consumption data points over a wide range of values. Six different sets of tires, including both radials and bias, were tested increasing the total data base and expanding

Figure 1


Carbon Balance Measurements (cc/km)
145.00
140.00
135.00
130.00
125.00
120.00
115.00
110.00
105.00
100.00
95.000
95.000
100.00
105.00
110.00
115.00
120.00
125.00
130.00
135.00
Fuel Flow Measurements (cc/km)

the range over which fuel consumption was observed. The same test sequence was used each time.

Each day a dynamometer and vehicle warm-up was conducted prior to the testing. This was considered necessary to minimize variations due to test equipment from day to day. Each test point consisted of a 300 second steady state. After stabilizing at the steady state speed, the fuel flow meter and the exhaust sampling bag were simultaneously turned on. After about 300 seconds both were turned off completing the sampling interval. The fuel meter paper tape, carbon balance data, and dynamometer roll revolutions were then recorded for the data reduction and evaluation.

B. Data Reduction

The data reduction process simply transformed the carbon balance and flow meter data to a common system of units for comparison. In this report fuel consumption, in cc/km, was used for all comparisons. For the carbon balance method the exhaust gases are collected, and sampled. The hydrocarbons, carbon monoxide, and carbon dioxide are then measured from this sample. The amount of carbon in these gases and therefore, the amount of gasoline used is then calculated in the manner typically used in EPA fuel consumption calculations. These results are expressed in a fuel volume correct to a standard fuel temperature of 60 F. This fuel volume was then divided by the distance travelled, as measured from the dynamometer rear roll, to obtain a fuel consumption rate in cc/km.

The flow meter measurements of fuel consumption were obtained from the printed tape output of the flow meter. The fuel temperature at the beginning and end of each 5 minute test was also obtained from the printed paper tape. The average of these temperatures was used to correct the measured consumption to the standard temperature of 60 F. Again, the distance travelled as measured by the dynamometer roll revolutions was used to compute fuel consumption per kilometer placing the measurements on a equal basis.

C. Data Analysis

The scatter plot in Figure 1 presents the carbon balance fuel consumption plotted vs. the fuel consumption measured by the flow meter. The plot shows an apparent linear relationship between the two methods. To check this linearity the data was analyzed by regressions of the form.

$$F_{CB} = a + bF_{fm} \qquad (1)$$

and:

$$F_{CB} = a + bF_{fm} + CF_{fm}^{2} \qquad (2)$$

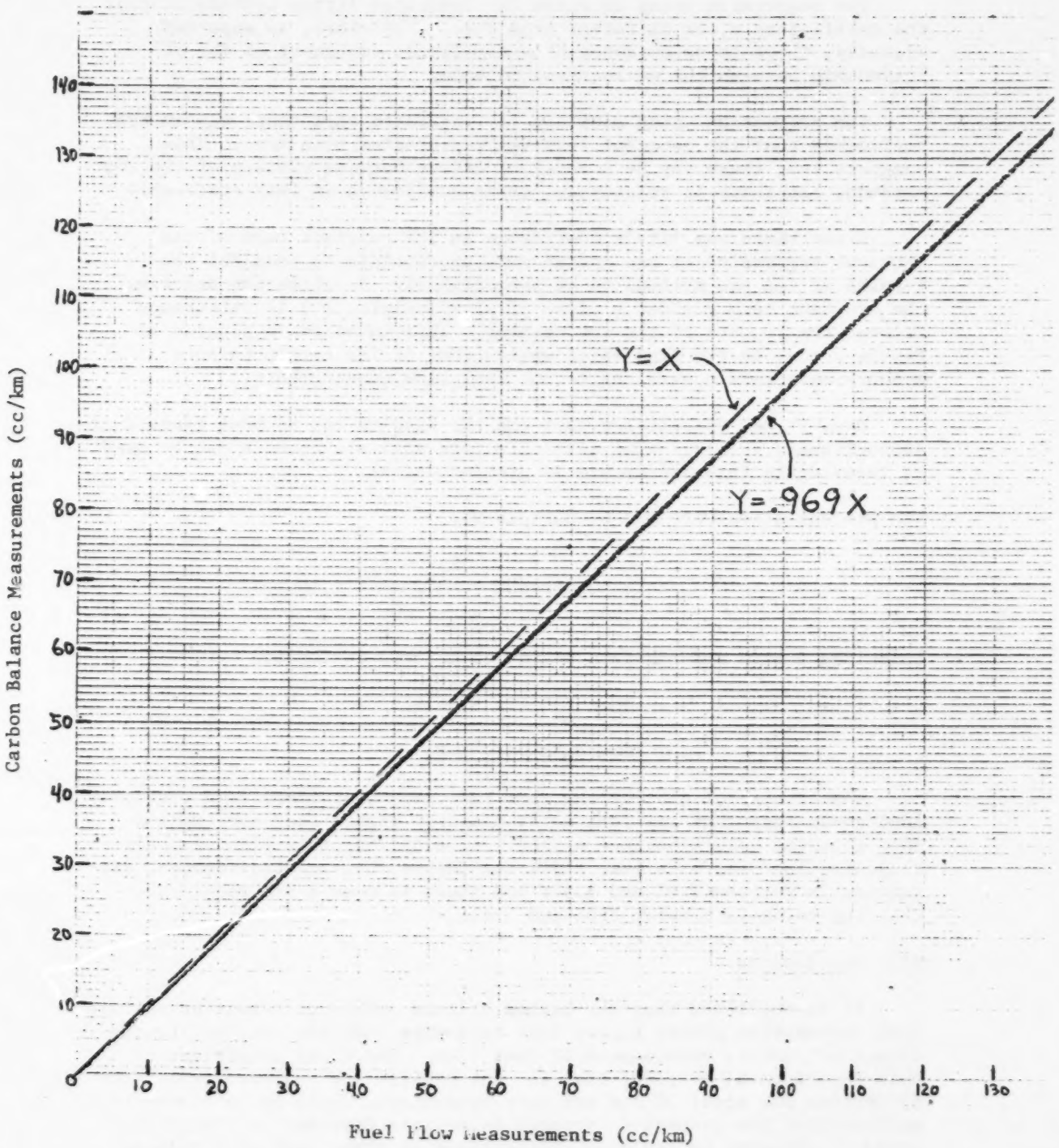
where:

F_{CB} = carbon balance fuel economy

F_{fm} = fuel flow meter fuel economy

a,b,c constants

Figure 2


Y=X
Y=.969X
Carbon Balance Measurements (cc/km)
Fuel Flow Measurements (cc/km)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140

The regression using equation (2) indicated little confidence that the coefficient, c, was different from zero. Therefore, as observed visually, there is no evidence of a non-linear component of the relationship between the measurement methods.

The regression using equation (1) indicated that there was an 85% confidence that the constant term (a) was greater than zero. This suggests that there may be a constant offset between results of the two methods, but there is relatively little confidence in this statement.

Since there was little confidence in the constant term of the previous regression it was judged more appropriate to consider the results of the two methods to be proportional. A regression deleting the constant term yielded a slope of .969 implying a 3.1% difference between the results of the two methods. This equation is plotted in Figure 2 next to the line which would occur if the carbon balance measurements were equivalent to the fuel flow measurements.

Once it was established that the two results can be best treated as proportional, the following alternate data analysis methods can be used to investigate this difference in greater detail:

The precent difference can be defined as:

$$\% \text{ Difference} = \frac{F_{fm} - F_{CB}}{F_{CB}} \times 100$$

Computing a mean and standard deviation of this variable:

Mean % Diff. = 3.12%

Standard Dev.=1.83

A students "t" test of the mean indicates that there is a virtually 100% confidence that the fuel meter measures higher fuel consumption than does the carbon balance method. In addition, this type of analysis indicates that there is over a 90% confidence that the true percent difference is between 2.9% and 3.5%; and there is over a 95% confidence that the value is between 2.8% and 3.6%.

III. Conclusions

It is concluded that the carbon balance method of measuring vehicle fuel consumption yields higher fuel economies than are obtained by the direct volumetric measurement of fuel flow. Under the conditions of this experimental program; that is, one vehicle and one test cell, the difference was about 3% and was very consistent. There is no reason to believe that the percent difference is vehicle dependent although it could be affected by analyzer calibrations or other test cell related parameters.

The flow meter had a rated accuracy of 0.5% and calibrations, immediately before the program confirmed that the measurement accuracy was within this range. In comparison, the carbon balance method requires several indirect calibrations and relies on several assumptions about the fuel composition. Therefore, the flow meter approach is probably the more accurate method of determining fuel consumption. Consequently, it is concluded that the carbon balance method overestimates the fuel economy of a vehicle by a small, but consistant amount. This conclusion is consistant with earlier EPA observations.(1)

IV. Recommendations

The observed difference between the carbon balance and fuel flow measurements, 3%, may seem small, however for the tested vehicle used it represents a composite fuel economy effect of about 0.5 mpg. Also, since the difference appears to be proportional to the fuel consumed, the difference between the two methods would be expected to be over 1 mpg in the case of a fuel efficient vehicle.

The first recommendation is to verify, by an independent measurement, which fuel consumption measurement approach is "correct". It is recommended that gravimetric measurements be obtained in parallel with the carbon balance and fuel flow measurements for this verification.

If it is verified that the carbon balance approach overestimates fuel economy, then the reason for the discrepancy should be identified. If it is a random calibration problem, not affecting all test cells, then it may be possible to easily correct the problem and reduce test variability. If it is a systematic problem, such as variations in fuel composition, then a change would require rulemaking and involve EPCA constraints. However, even in this case, it may be relatively easy to compute one set of fuel economies for EPCA compliance and a second set for the EPA label and buyer's guide.

As a first step in identifying the case of the discrepancies, it is recommended that measurements be obtained over a wide range of fuel consumptions to resolve if the differences are truly proportional, as indicated by this experiment, or if some constant offset may also exist.

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1 Christopher Marzonie, Memorandum to Charles Gray, "Accuracy of Fuel Economy Measurements", August 1977.

☆ U.S. GOVERNMENT PRINTING OFFICE: 1980- 651-112/0143